LEVEL II

1

AD A109321

DTIC FILE COPY

THE NUMERICAL SIMULATION OF CRACK GROWTH IN WELD-INDUCED RESIDUAL STRESS FIELDS

by

M.F. Kanninen, F.W. Brust, J. Ahmad, and I.S. Abou-Sayed

STRESS ANALYSIS AND FRACTURE SECTION

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

July, 1981

DTIC
ELECTE
JAN 5 1982
S D
D

407080

Invited paper for the 28th Army Sagamore Research Conference, Lake Placid, New York, July 13-17, 1981. To appear in the Conference Proceedings.

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

82 01 04 060

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO. AD-A10 9 321

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
THE NUMERICAL SIMULATION OF CRACK GROWTH IN WELD-INDUCED RESIDUAL STRESS FIELDS

5. TYPE OF REPORT & PERIOD COVERED
Interim

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
M.F. Kanninen, F.W. Brust, J. Ahmad, and I.S. Abou-Sayed

8. CONTRACT OR GRANT NUMBER(s)
N00014-77-C-0576 - Battelle

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Battelle's Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research
Structural Mechanics Program
Department of the Navy, Arlington, VA 22217

12. REPORT DATE
March 1981

13. NUMBER OF PAGES
22

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES
Paper was presented at the 28th Army Sagamore Research Conference, Lake Placid, New York, July 13-17, 1981.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Stress Corrosion Cracking; Fracture; Dynamic Crack Propagation, Finite Element Analyses

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
A marriage of elastic plastic fracture mechanics techniques with thermoplastic finite element analyses is developed to examine crack growth in the presence of weld-induced residual stresses. A hypothetical crack growth relation based on the crack tip opening displacement is used. Three problem areas are studied: stress corrosion cracking in a girth-welded pipe, fatigue crack growth under cyclic loading in a butt-welded plate, and dynamic crack propagation under impact loading in a butt-welded plate. Comparisons with computations carried out under conventional linear elastic assumptions are made. It is found that, in all three

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE (over)

S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

cases, neglect of the plastic deformation caused by the welding process appears to be anti-conservative. It is concluded that more realistic computations for crack growth in and around welds than are commonly used may be needed for realistic structural integrity assessments.

Accession For
NTIS GRA&I ☒
DTIC TAB ☐
Unannounced ☐
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or Special

THE NUMERICAL SIMULATION OF CRACK GROWTH IN WELD-INDUCED RESIDUAL STRESS FIELDS

M. F. Kanninen, F. W. Brust,
J. Ahmad, and I. S. Abou-Sayed
Stress Analysis and Fracture Section
Battelle Columbus Laboratories
Columbus, Ohio 43201

ABSTRACT

A marriage of elastic-plastic fracture mechanics techniques with thermoplastic finite element analyses is developed to examine crack growth in the presence of weld-induced residual stresses. A hypothetical crack growth relation based on the crack tip opening displacement is used. Three problem areas are studied: stress corrosion cracking in a girth-welded pipe, fatigue crack growth under cyclic loading in a butt-welded plate, and dynamic crack propagation under impact loading in a butt-welded plate. Comparisons with computations carried out under conventional linear elastic assumptions are made. It is found that, in all three cases, neglect of the plastic deformation caused by the welding process appears to be anti-conservative. It is concluded that more realistic computations for crack growth in and around welds than are commonly used may be needed for realistic structural integrity assessments.

INTRODUCTION

A significant proportion of all structural failures can be traced to cracks emanating in and around welds. Crack growth in welded regions must be strongly affected by the presence of the plastically deformed material indigenous to the welding process. Yet, present day fracture mechanics analysis procedures, which are largely based on linear elastic conditions, do not directly treat such complications. While elastic-plastic fracture mechanics analysis procedures have been developed, they have previously been

applied to account only for crack tip plasticity itself. Recently, a further step has been taken by the authors through the use of postulated elastic-plastic crack growth relations for crack growth in weld-induced plastic deformation fields[1-3]. This work is summarized and assimilated in this paper.

The immediate objective of the work reported in References 1-3 was to critically examine the assumptions of linear elastic material behavior commonly made in analyzing weld cracking problems. Three separate problems were addressed. As shown in Table 1, these included two different welded structures - a girth-welded pipe and a butt-welded plate - and three different crack growth mechanisms - stress corrosion, fatigue and unstable crack propagation. The solution procedure and the individual results are first presented in what follows with general conclusions for future progress in the analysis of crack growth in the presence of weld-induced residual stress drawn from them.

Table 1. Problems Examined

Structure	Material	Applied Loading	Simulated Cracking Mechanism
Girth-welded pipe with circumferential crack (axisymmetry)	Type 304 Stainless Steel	Constant Tension	Stress Corrosion
Butt-welded with edge crack (Plane Strain)	HY-80 Steel	Cyclic Tension	Fatigue
Butt-welded plate with edge crack (Plane Strain)	HY-80 Steel	Impulsively Applied Tension	Dynamic Fracture

THE ANALYSIS PROCEDURE

The analysis procedure followed in this work, which is basically the same for all three problems examined, consists of three main steps:

1. The residual stress field induced in a welding process is computed using an incremental thermoplastic finite element analysis procedure.

2. Crack growth is simulated by sequential node release along a pre-set crack plane located in the weld heat-affected zone.

3. A postulated elastic-plastic crack growth relation is used to infer crack length as a function of time or loading history to simulate a particular crack mechanism.

A comparison with a computational result made using a commonly accepted linear elastic approach is then made to assess the significance of the linear elastic assumption and the essential neglect of residual plasticity inherent in such an approach.

Residual Stress Analysis

The residual stress analysis procedure is one that has been used successfully at Battelle in a variety of applications[4-6]. It consists of two parts. First, a thermal analysis is made to obtain the time-temperature history for each point in the body for each individual welding pass. Then, these histories are used as input to an incremental elastic-plastic finite element model to determine the stress and deformation state of the weld and the base material as the weld is deposited. Because each welding pass is considered on an individual basis, the residual stress and strain state that exists at the completion of one weld pass constitutes the initial condition for the next. The final residual stress state is that which exists at the completion of all of the weld passes.

In the work described here, the finite element models for the welding analysis were designed with a line of double nodes along a pre-set crack plane. This had no effect on the residual stress distribution as it was assumed that an initial (small) crack appeared after the welding process was complete[7]. The potential crack plane was located in the heat-affected zone but was otherwise arbitrary.

The two welded structures examined in the work reported here - a girth-welded pipe and a butt-welded plate - are shown in Figures 1 and 2, respectively. The corresponding finite element models are shown in Figures 3 and 4. It can be seen that a number of simplifications have been introduced for computation convenience. These include:

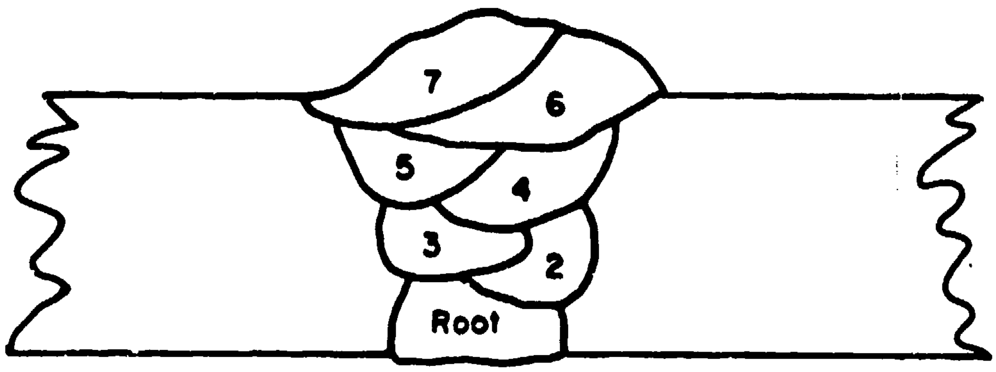

FIGURE 1. CROSS SECTION OF A SEVEN-PASS GIRTH-BUTT WELD IN A 4-INCH DIAMETER SCHEDULE 80 TYPE 304 STAINLESS STEEL PIPE

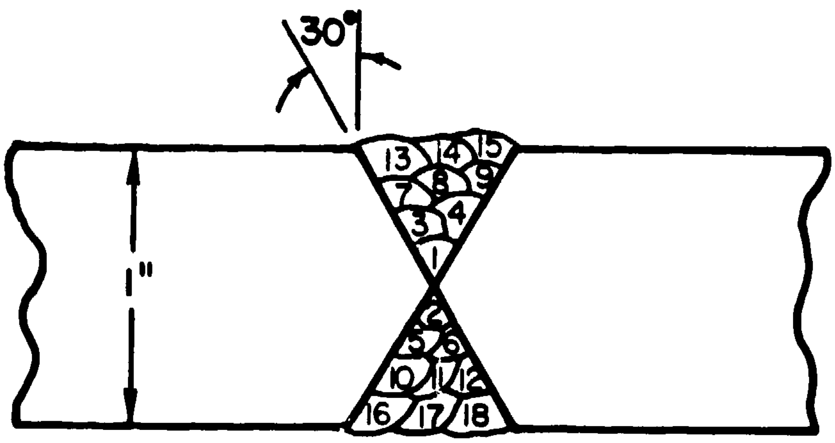

FIGURE 2. CROSS SECTION OF AN 18-PASS BUTT WELD IN AN HY-80 STEEL SHIP STRUCTURE

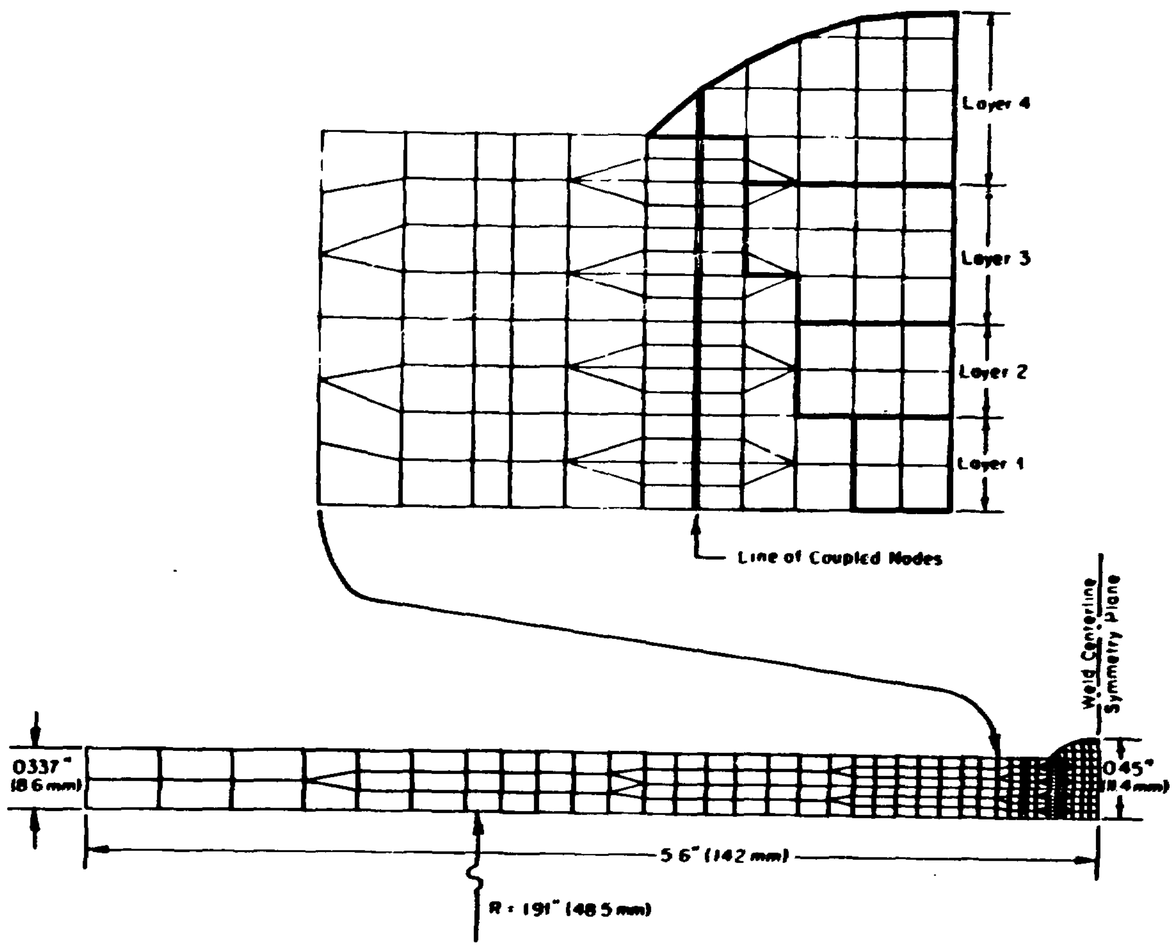

FIGURE 3. FINITE ELEMENT MODEL FOR RESIDUAL STRESS AND CRACK GROWTH ANALYSIS IN A GIRTH-WELDED 4-INCH DIAMETER SCHEDULE 80 TYPE 304 STAINLESS STEEL PIPE

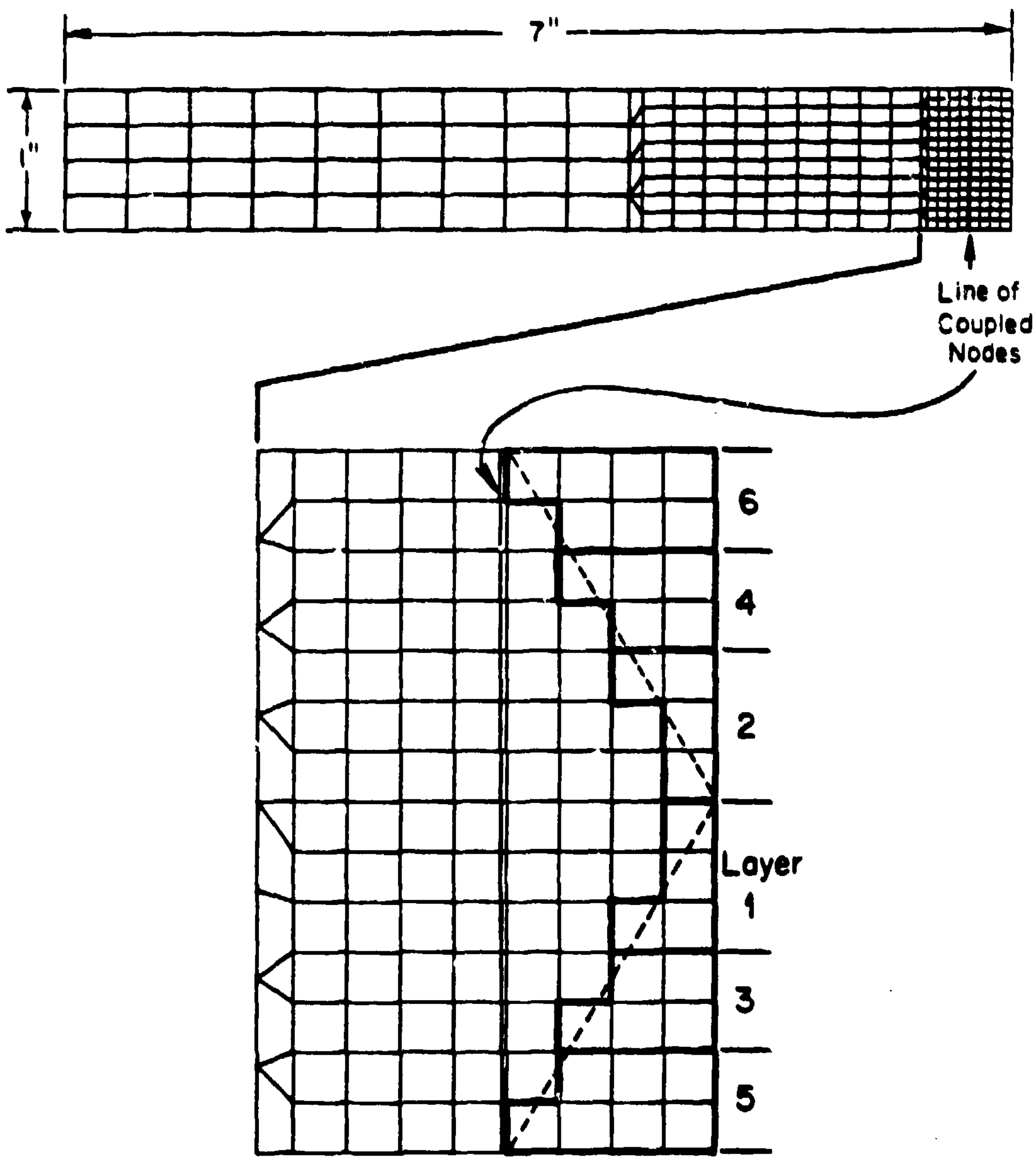

FIGURE 4. FINITE ELEMENT MODEL FOR A BUTT-WELDED PLATE (PLANE STRAIN)

- weld line symmetry

- two-dimensional deformation (i.e., axisymmetry or plane strain)

- one-dimensional crack growth (i.e., concentric or collinear).

Note that, because the cracks are not supposed to be at the center of the weld (cf, Figures 3 and 4), the first of these simplifying assumptions means that two cracks exist in the analysis.

The temperature-dependent material properties used in the analyses of the pipe weld are those of Type 304 stainless steel shown in Figure 5. The properties for the butt-welded plate are those of the ship structure steel HY-80 given in Figure 6. In the first problem, the heat inputs were taken from an actual experience[7] while in the second, typical values were used. These together with the weld pass and structure geometry, suffice to determine the residual stress distribution. The normal stresses acting on the prospective crack plane for the two welded configurations are shown in Figures 7 and 8. It can be seen that, while these are quite different, they share a high tensile stress near the surface. Thus, an edge crack would be likely to grow, particularly when the residual stresses are abetted by a tensile applied stress.

Subcritical Crack Growth Analysis

The equivalence between the crack tip opening displacement (CTOD) and the stress intensity factor in small-scale yielding is well known. Recent progress in elastic-plastic fracture mechanics has further revealed the distinctive role played by the crack tip crack opening displacement in crack initiation and stable growth in large scale yielding conditions[8-10]. Specifically, for the initiation of crack growth, the CTOD can be expressed as

$$\delta = \begin{cases} \alpha \dfrac{K^2}{EY} & \text{small-scale yielding} \\[2ex] d_n \dfrac{J}{Y} & \text{deformation plasticity} \end{cases} \qquad (1)$$

where K is the stress intensity factor, J is the J-integral parameter, E is the elastic modulus, Y is the yield stress while α and d_n are numerical constants on the order of unity. In addition, for extended stable crack growth, the CTOD appears to take on a constant value. While certainly not conclusive evidence that the

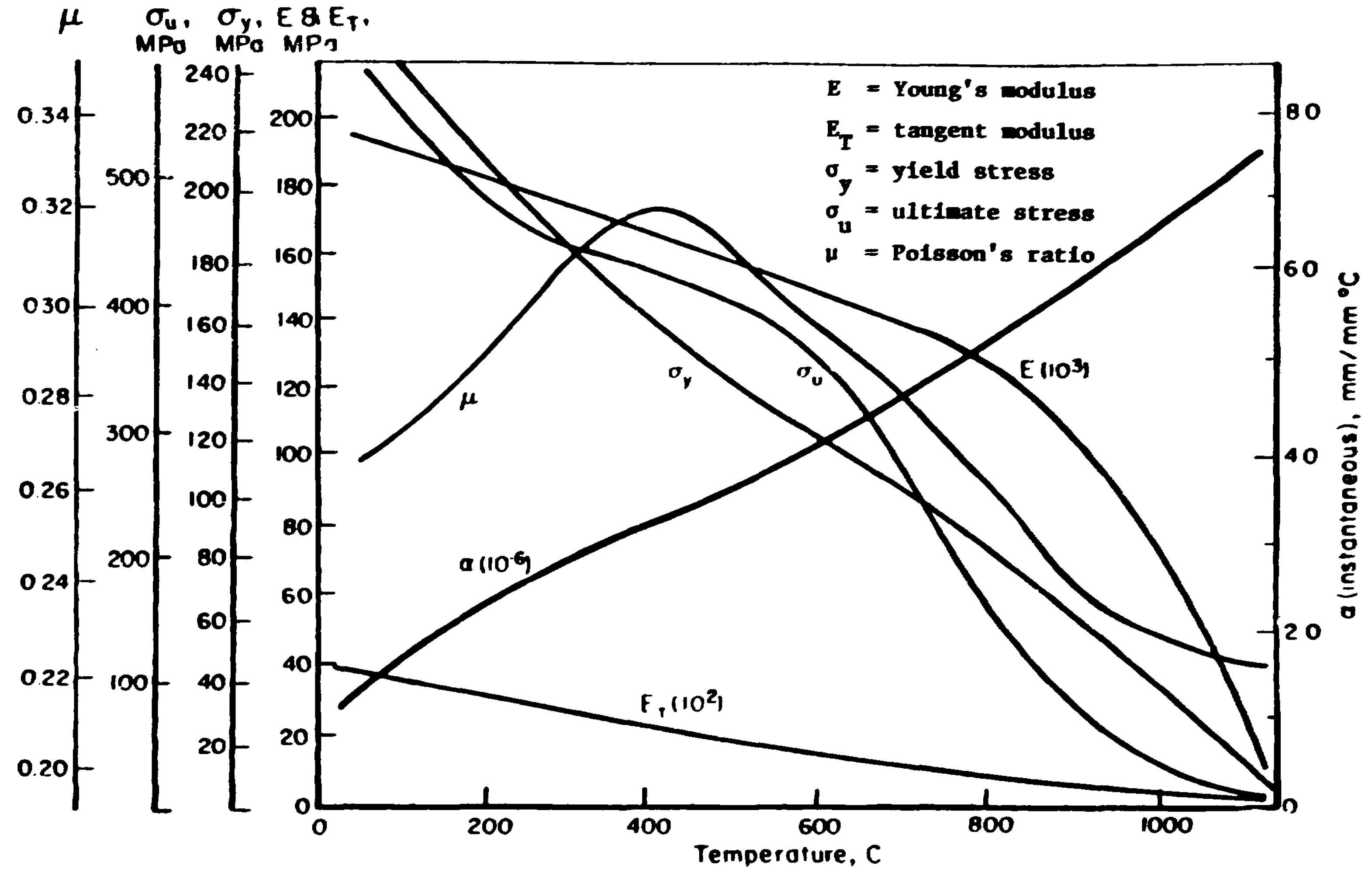

FIGURE 5. TEMPERATURE DEPENDENT PROPERTIES OF TYPE 304 STAINLESS STEEL

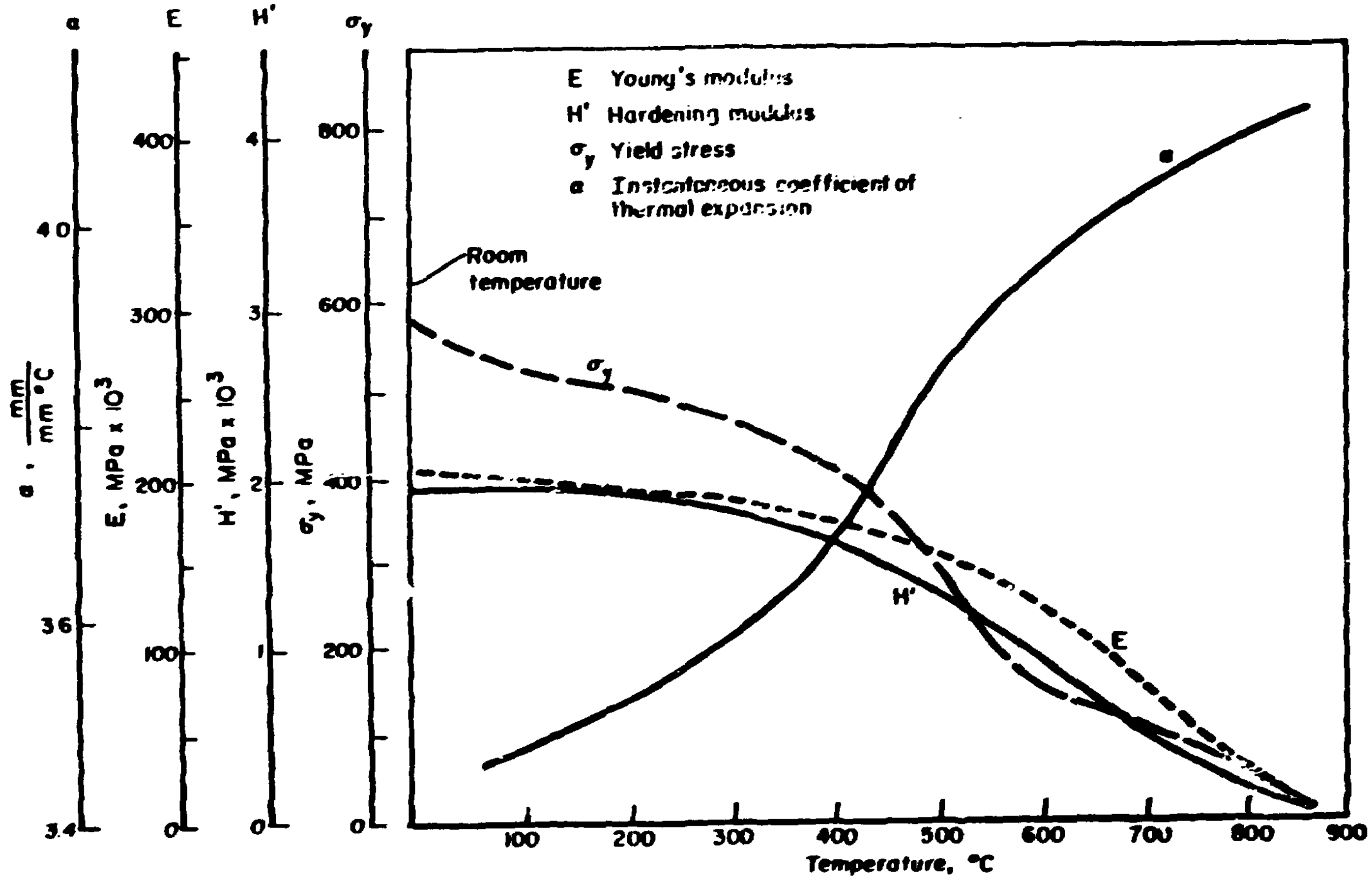

FIGURE 6. TEMPERATURE DEPENDENT MATERIAL PROPERTIES FOR HY-80

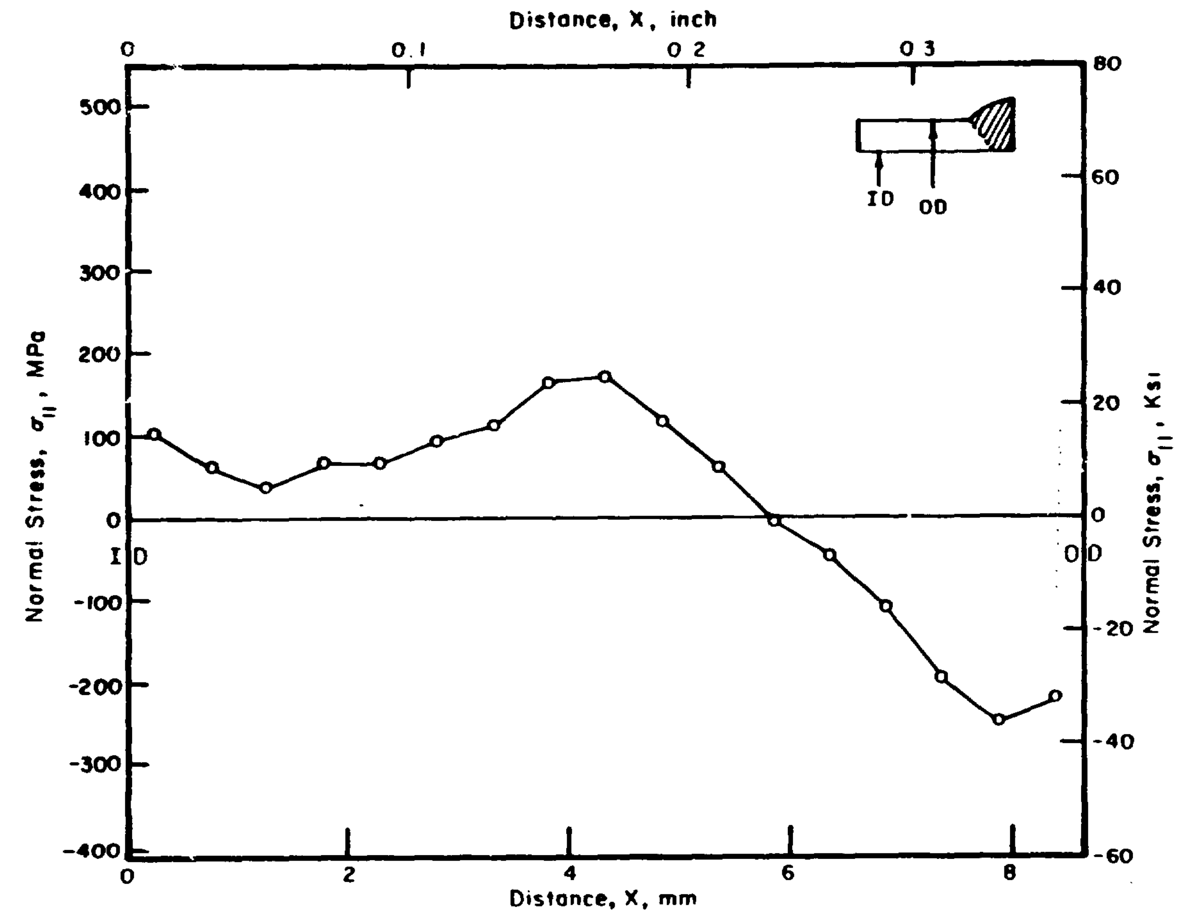

FIGURE 7. THROUGH-WALL RESIDUAL STRESSES ON THE POTENTIAL CRACK LINE IN A GIRTH-WELDED 4-INCH DIAMETER PIPE

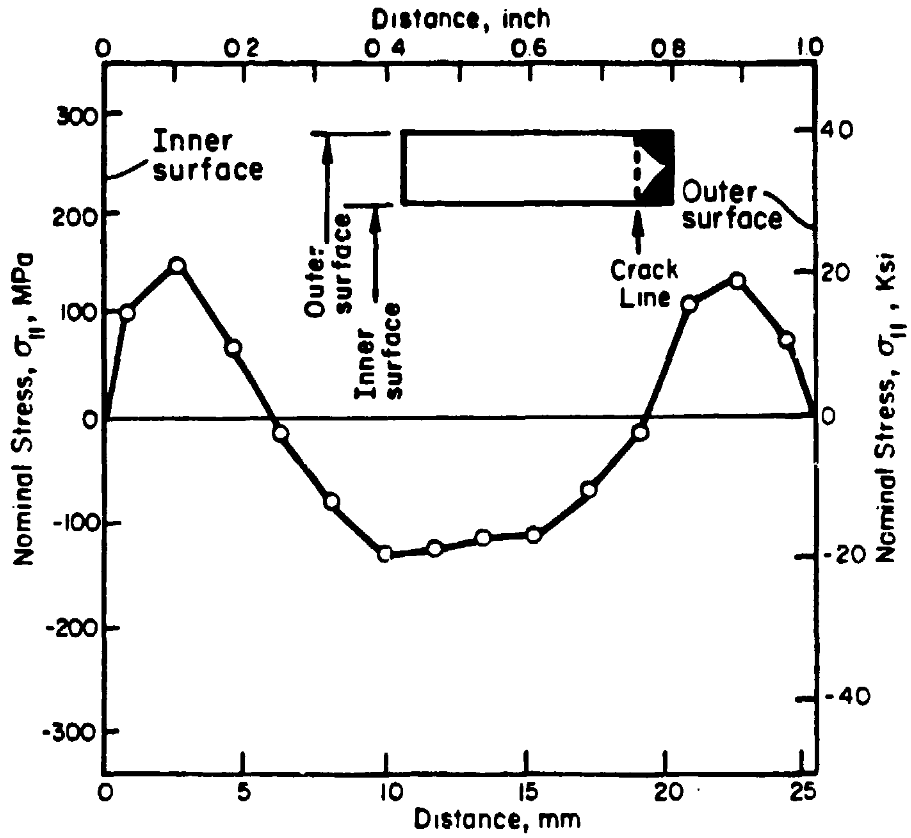

FIGURE 8. RESIDUAL STRESS ON POTENTIAL CRACK LINE IN A 1-INCH THICK BUTT-WELDED PLATE OF HY-80 STEEL

CTOD is the controlling parameter for subcritical crack growth as well, for lack of an alternative, it will be so taken in this work. Note that, because of the equivalence represented by Equation (1), this choice is not inferior to one based on either K or J in any event.

Starting from an assumed initial crack, crack growth is simulated in each of the finite element models by sequential node release along the line of double-noded elements. Each node pair is released by diminishing the initial force that exists between them to zero. This is done over from five to ten load increments. The value of δ for a given crack length is then the value of the CTOD that exists when the load has vanished. Hence, it is a value at one finite element spacing behind the actual crack tip. The results obtained from the finite element models are shown in Figures 9 and 10. Note that in the latter problem two solutions are shown: one with no applied stress, the second with an applied tensile stress normal to the crack plane of 67 percent of the room temperature yield stress of HY-80 steel (80 ksi).

Figures 9 and 10 contrast the CTOD values obtained by advancing the crack through the finite element model under two different conditions. First, the computed weld-induced plastic deformation is left unaltered and an incremental plasticity computation made. This is the elastic-plastic analysis. Second, a simplified approach is followed wherein (1) only the normal component of the residual stress acting on the potential crack plane is retained, and (2) linear elastic behavior is assumed. This is denoted as the simple elastic analysis and typifies that commonly used for this kind of problem.

Stress corrosion cracking is often supposed to occur according to a power law relation of the type

$$\frac{da}{dt} = CK^m \tag{2}$$

where a denotes the crack length, t is time, while C and m are material constants. Because this relation is clearly valid only under small scale yielding conditions, the relation between K and δ expressed by Equation (1) can be used to cast it into the equivalent form

$$\frac{da}{dt} = C'\delta^{m/2} \tag{3}$$

where C' is also a material constant[1]. Having $\delta = \delta$ (a) from Figure 9, Equation (3) can be integrated numerically to find the crack length in terms of a dimensionless time t*

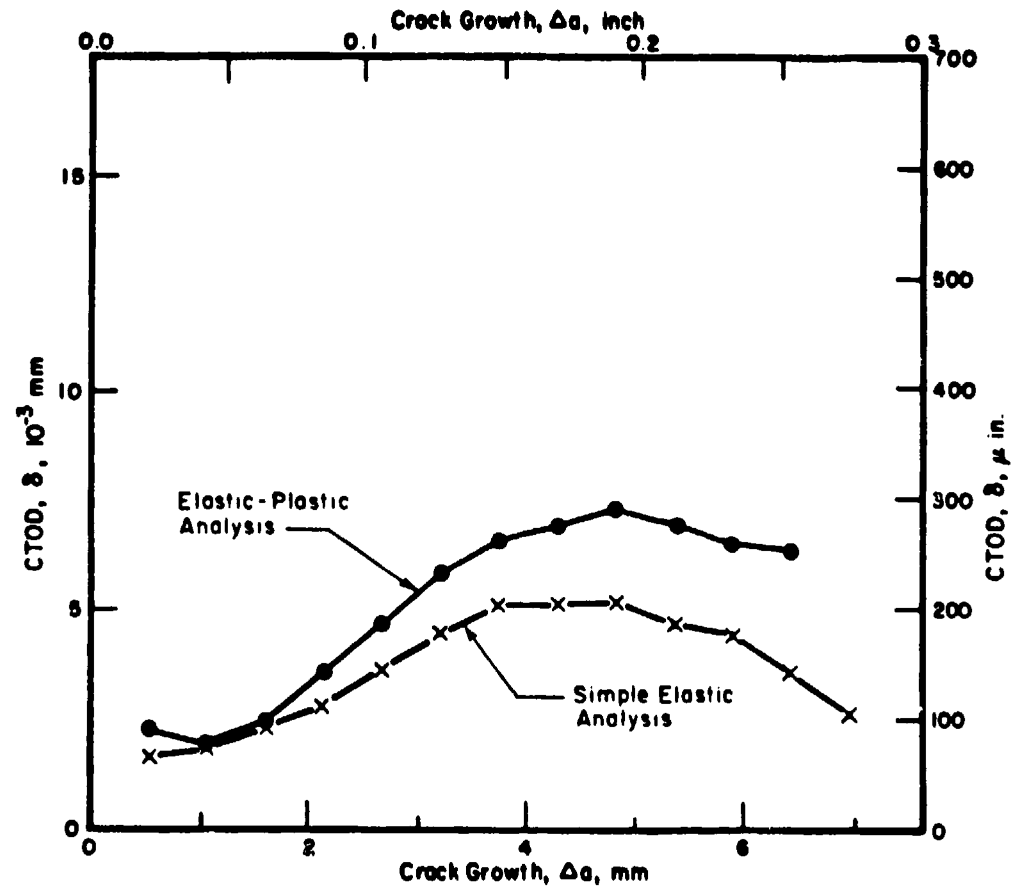

FIGURE 9. CTOD CALCULATED AS A FUNCTION OF CRACK GROWTH (Δa) FOR 4-INCH DIAMETER TYPE 304 STAINLESS STEEL PIPE SUBJECTED TO WELDING INDUCED RESIDUAL STRESSES AND ZERO APPLIED STRESS

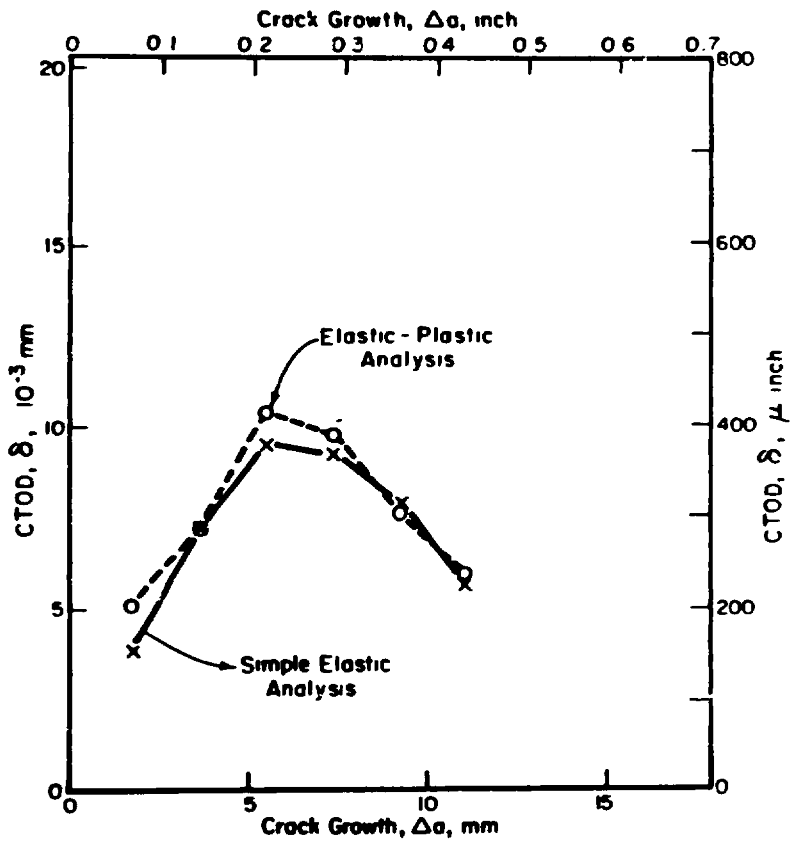

FIGURE 10 (a). ZERO APPLIED LOAD

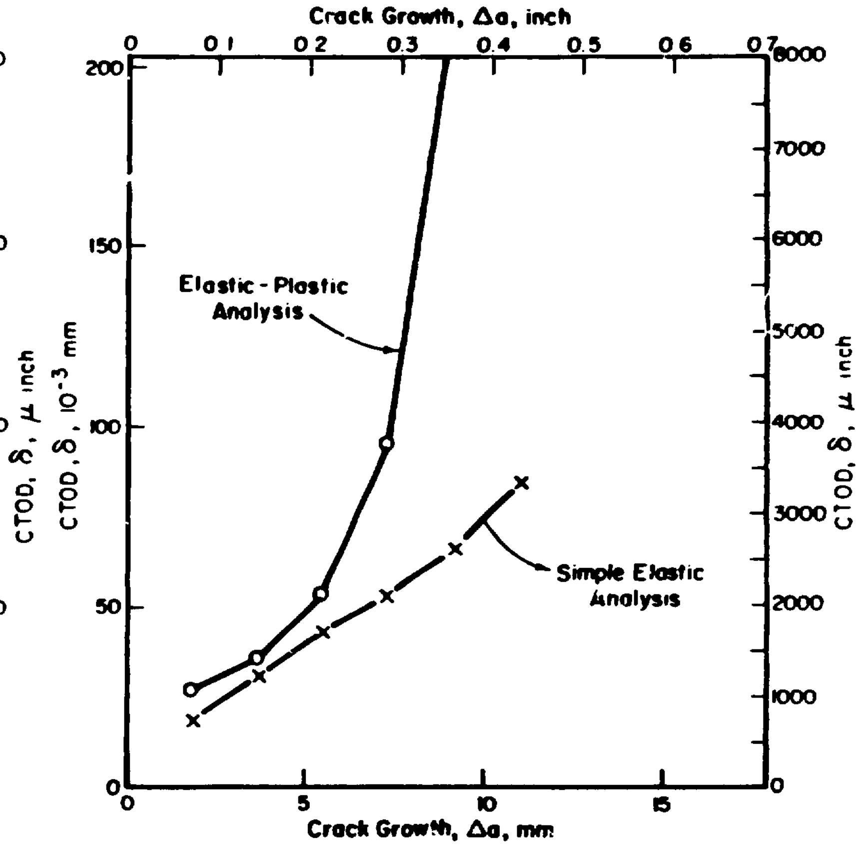

FIGURE 10 (b). APPLIED LOAD = 0.67 σ_o

COMPUTED CRACK TIP OPENING DISPLACEMENT IN A BUTT-WELDED HY-80 PLATE AS A FUNCTION OF CRACK GROWTH

$$t^* = \int_{a_o}^{a} \frac{h^{m/2-1}}{\delta^{m/2}}\, da \qquad (4)$$

where h denotes the wall thickness. The result is shown in Figure 11.

Notice that the results given in Figure 11 were obtained without the imposition of an applied stress. Thus, despite the fact that the residual stresses are self-equilibrating, catastrophic crack growth can occur. The reason is that the stresses are redistributed as crack growth occurs and, at least until a net compressive force is freed by the growing crack, a positive crack driving force exists; cf, Figure 9. Of more importance, the results of Figure 11 indicate that the simple elastic analysis predicts an anti-conservative result in that the time-to-failure is greater than in the more rigorous elastic-plastic analysis.

Fatigue crack growth under a uniform cyclic loading can often be adequately characterized in the form

$$\frac{da}{dN} = C\,(K_{max} - K_{min})^m \qquad (5)$$

where N denotes a load cycle number and C and m are material constants. Again introducing the CTOD from Equation (1) gives

$$\frac{da}{dN} = C'(\delta_{min}^{1/2} - \delta_{min}^{1/2})^m \qquad (6)$$

where δ_{max} and δ_{min} are the CTOD values that would be attained under the maximum and minimum load levels, respectively. Consequently, the number of cycles required to achieve a given crack length can be found by integrating Equation (6) via

$$N = \frac{1}{C'} \int_{a_o}^{a} \frac{da}{(\delta_{max}^{1/2} - \delta_{min}^{1/2})^m} \qquad (7)$$

The results, using the CTOD values given in Figure 10, are shown in Figure 12. It can be seen that the simple elastic analysis is once again anti-conservative.

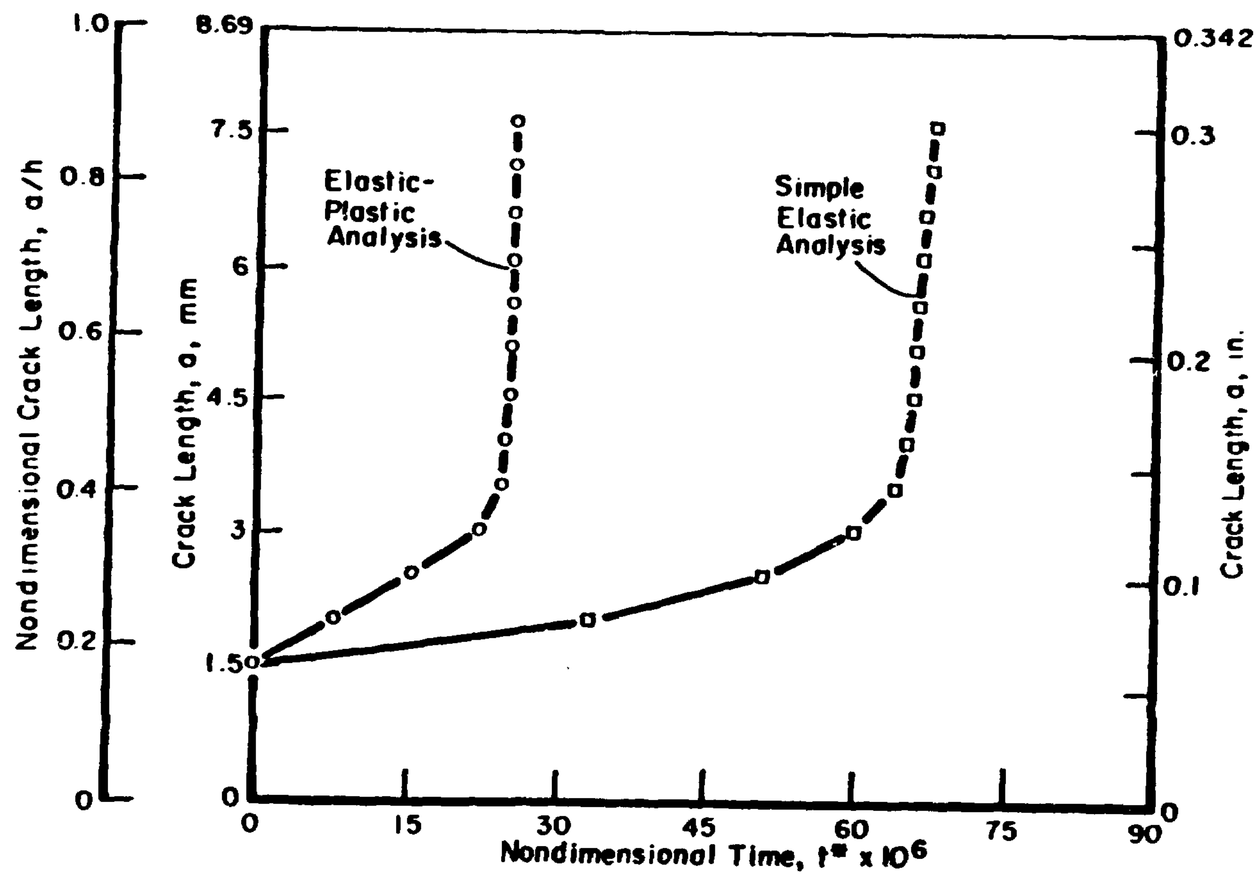

FIGURE 11. NONDIMENSIONAL TIME t* AS A FUNCTION OF CRACK GROWTH FOR 4-INCH DIAMETER TYPE 304 STAINLESS STEEL PIPE SUBJECTED TO WELDING INDUCED RESIDUAL STRESSES

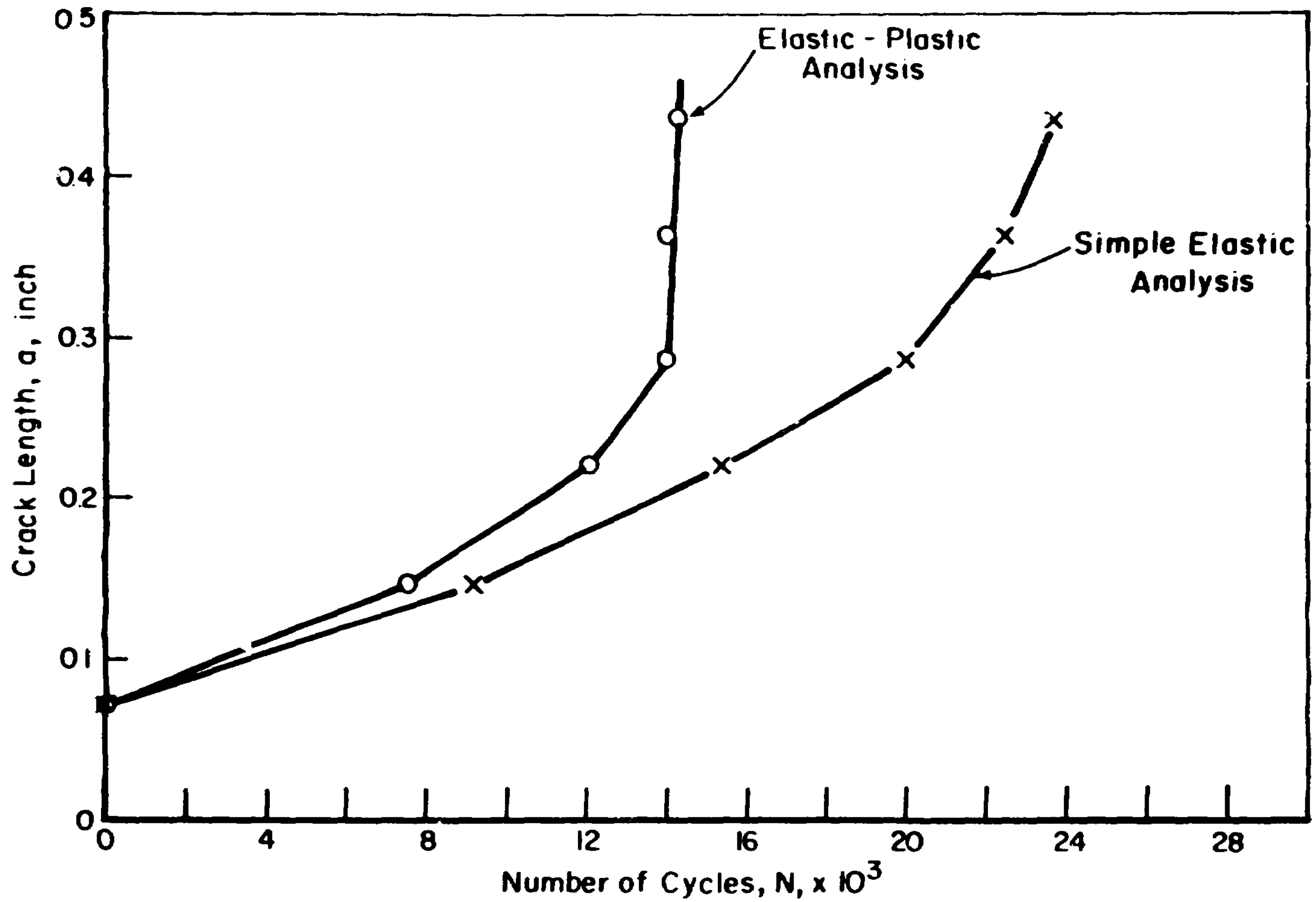

FIGURE 12. COMPARISON OF ELASTIC AND ELASTIC-PLASTIC COMPUTATION OF FATIGUE CRACK GROWTH IN A BUTT-WELDED PLATE

Dynamic Crack Propagation Analysis

The governing relations for unstable crack propagation and arrest in elastodynamic conditions are

$$K = K_D \ , \ \dot{a} > 0$$
$$K < K_D \ , \ \dot{a} = 0 \tag{8}$$

where K_D is known as the dynamic fracture toughness. Once again, so long as small scale yielding conditions are satisfied, such relations are equivalent to those couched in terms of the CTOD. In particular, the critical CTOD value for dynamic crack propagation would then be simply

$$\delta_D = \alpha \frac{K_D^2}{EY} \tag{9}$$

Clearly, if a time varying loading is imposed on a cracked body, the CTOD value will also vary. So long as $\delta < \delta_D$, the crack tip will be stationary. If δ becomes equal to δ_D, crack growth will occur at a rate such that the equality is maintained. Arrest occurs when the equality can no longer be satisfied.

A dynamic computation was performed in which the ship structure shown in Figure 2 was subjected to a suddenly imposed load of 42 ksi, about 50 percent of the room temperature yield stress. This load was held for 30 μsec and then dropped to zero. A value of $K_c = 37.9$ ksi$\sqrt{\text{in.}}$ was used to reflect the lower toughness existing in the heat-affected zone. Using Equation (9), this gave a critical CTOD value of 0.0006 inch. Both a linear elastodynamic and an elastic-plastic dynamic calculation were made. The elastic-plastic analysis was based on the entire residual stress and deformation field together with incremental dynamic plasticity. However, in accord with common practice, the residual stresses were completely ignored in the elastic analysis. The computed CTOD values for the two analyses are shown in Figure 13.

It can be seen in Figure 13 that the elastic-plastic analysis predicts that unstable crack growth would quickly occur (at approximately 15 μsec). It also predicts that the crack would penetrate the wall. In contrast, the elastic analysis does not predict initiation of growth until much later (about 40 μsec) and predicts arrest soon thereafter. Consequently, the simpler procedure is once again found to be anti-conservative.

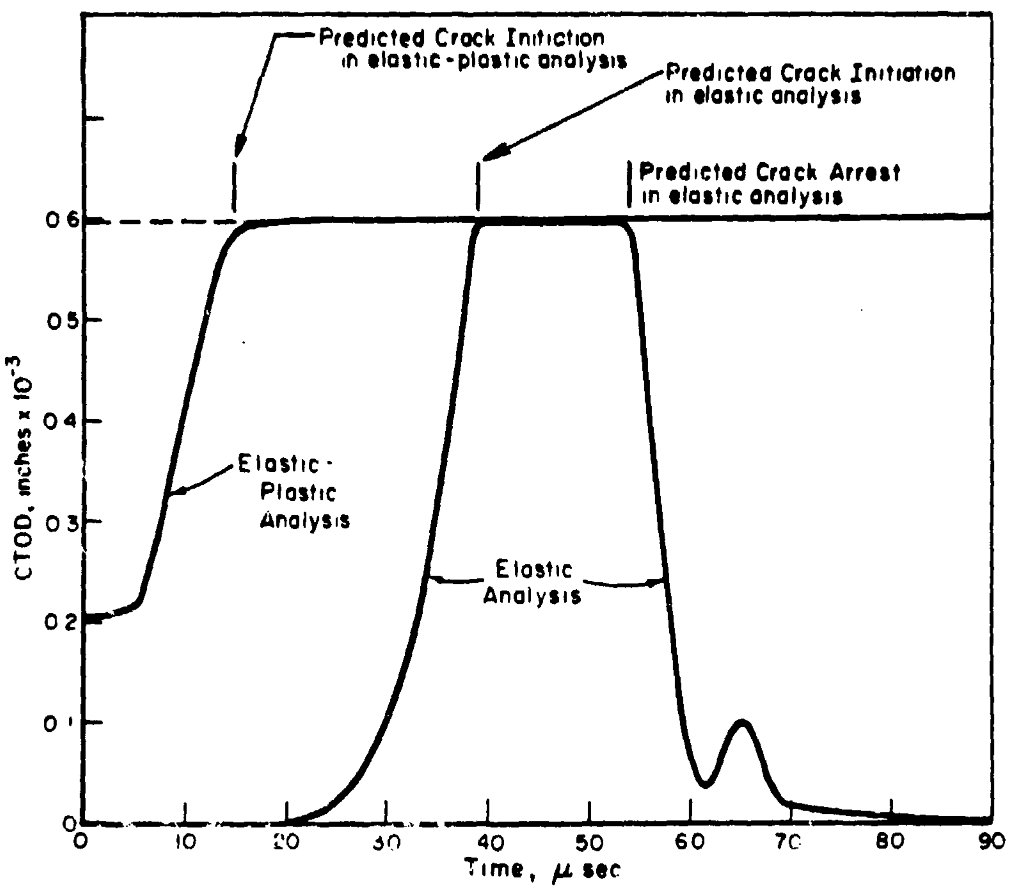

FIGURE 13. COMPARISON OF ELASTIC AND ELASTIC-PLASTIC SOLUTIONS FOR DYNAMIC CRACK PROPAGATION IN THE HEAT AFFECTED ZONE OF AN INITIALLY CRACKED BUTT-WELDED PLATE

DISCUSSION

It is important to recognize that the prime purpose of this work was not to arrive at quantitative results for different types of material behavior. Rather, it was to critically examine a set of assumptions that are commonly used in analyzing a class of problems for given material behavior. The specific materials considered in this study are very ductile and tough (e.g., Type 304 stainless steel, HY-80 steel) which undoubtedly exacerbates the differences that were found. It is quite possible that other materials--and, perhaps more importantly, residual stress fields induced without large-scale plastic deformations--would show considerably less difference. Of equal importance, since the elastic-plastic crack growth criteria needed for the purposes of this study have not been established, a pragmatic approach was taken to obtain comparative results. All of these factors would be borne in mind in interpreting the results given in this paper.

The basic assumption that has been called into question here is the applicability of linear elastic fracture mechanics in the presence of weld-induced residual stress fields. This has been addressed by performing two parallel computations where this assumption has and has not been made. Hence, while there are undeniably many aspects of the calculations that can be improved upon, because the two computations were otherwise performed on exactly the same basis, these cannot be of critical importance. Indeed, the comparison has revealed such wide disparities, that, neglect of the inelastic deformation accompanying welding would appear to be unequivocally incorrect.

Conversely, the work presented in this paper should not be taken as a blanket indictment of LEFM-based crack growth predictions. The mathematical convenience of LEFM is too useful to not play an important part in the assessment of weld cracking. What appears to be needed is some sort of plasticity-enhanced LEFM procedure, possibly calibrated with the more rigorous analyses described in this paper, that can be confidently applied even in the presence of large-scale plasticity and its attendant residual stress fields. How this can best be done is an open question at this time. However, as the work reported herein so strongly suggests, the necessity for it is not.

CONCLUSIONS

Elastic-plastic fracture mechanics research has identified the CTOD as a key crack growth parameter. The use of this finding in conjunction with thermoplastic finite element analysis procedures has enabled more realistic computations of crack growth in the

presence of weld-induced residual deformation and stresses to be made. Comparisons of these results with commonly used approaches based on linear elastic fracture mechanics indicate that the latter could be highly anti-conservative.

ACKNOWLEDGEMENT

This paper was prepared with support from the structural mechanics program of the Office of Naval Research under Contract Number N-00014-77-C-0576. The authors would like to express their gratitude to Drs. N. Perrone and Y. Rajapakse of ONR for supporting their work.

REFERENCES

1. I. S. Abou-Sayed, J. Ahmad, F. W. Brust, and M. F. Kanninen, "An Elastic-Plastic Fracture Mechanics Prediction of Stress Corrosion Cracking in a Girth-Welded Pipe", 14th ASTM National Symposium on Fracture Mechanics, Los Angeles, June 30 to July 2, 1981.
2. F. W. Brust, J. Ahmad, V. Papaspyropoulos, and M. F. Kanninen, "An Elastic-Plastic Fracture Mechanics Prediction of Fatigue Crack Growth in the Heat-Affected Zone of a Butt-Welded Plate", manuscript in preparation (July, 1981).
3. J. Ahmad, F. W. Brust, and M. F. Kanninen, "Dynamic Crack Propagation in the Heat-Affected Zone of an Impact-Loaded Butt-Welded Plate", manuscript in preparation (July, 1981).
4. E. F. Rybicki, D. W. Schmueser, R. G. Stonesifer, J. J. Groom, and H. W. Mishler, "Residual Stresses at Girth-Butt Welds in Pipes and Pressure Vessels", Battelle's Columbus Laboratories Report to the U.S. Nuclear Regulatory Commission, NUREG-0376 (November, 1977).
5. F. W. Brust and R. B. Stonesifer, "Effect of Weld Parameters on Residual Stresses in BWR Piping Systems", Battelle's Columbus Laboratories Report to the Electric Power Research Institute on RP1174 (June, 1980).
6. M. F. Kanninen, T. E. Barber, F. W. Brust, and H. W. Mishler, "Controlling Residual Stresses by Heat Sink Welding", Battelle's Columbus Laboratories Report to the Electric Power Research Institute on RP1576-1 (December, 1980).
7. W. J. Shack, W. A. Ellingson, and L. E. Pahis, "The Measurement of Residual Stresses in Type 304 Stainless Steel Pipe Butt Weldments", Argonne National Laboratory Report to the Electric Power Research Institute on RP449-1 (December, 1978).

8. M. F. Kanninen, et al, "The Development of a Plastic Fracture Methodology", Battelle's Columbus Laboratories Report to the Electric Power Research Institute on RP601-1, EPRI NP-1734 (March, 1981).
9. C. F. Shih, et al, "Methodology for Plastic Fracture", General Electric Company Report to the Electric Power Research Institute on RP601-2, EPRI NP-1735 (March, 1981).
10. M. F. Kanninen, C. H. Popelar, and D. Broek, "A Critical Survey on the Application of Plastic Fracture Mechanics to Nuclear Pressure Vessels and Piping", Battelle's Columbus Laboratories Report to the U.S. Nuclear Regulatory Commission, NUREG CR-2110 (May, 1981).